Autonomous Control Modes and Optimized Path Guidance for Shipboard Landing in High Sea States

Progress Report (CDRL A001)

Progress Report for Period: Nov 10, 2016 to Jan 9, 2017

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Section I: Project Summary

1.   Overview of Project

This project is performed under the Office of Naval Research program on Basic and Applied Research in Sea-Based Aviation (ONR BAA12-SN-0028). This project addresses the Sea Based Aviation (SBA) initiative in Advanced Handling Qualities for Rotorcraft.

Landing a rotorcraft on a moving ship deck and under the influence of the unsteady ship airwake is extremely challenging. In high sea states, gusty conditions, and a degraded visual environment, workload during the landing task begins to approach the limits of a human pilot's capability. It is a similarly demanding task for shipboard launch and recovery of a VTOL UAV. There is a clear need for additional levels of stability and control augmentation and, ultimately, fully autonomous landing (possibly with manual pilot control as a back-up mode for piloted flight). There is also a clear need for advanced flight controls to expand the operational conditions in which safe landings for both manned and unmanned rotorcraft can be performed. For piloted rotorcraft, the current piloting strategies do not even make use of the available couplers and autopilot systems during landing operations. One of the reasons is that, as the deck pitches and rolls in high sea states, the pilot must maneuver aggressively to perform a station-keeping task over the landing spot. The required maneuvering can easily saturate an autopilot that uses a rate limited trim system. For fly-by-wire aircraft, there is evidence that the pilot would simply over-compensate and negate the effectiveness of a translation rate command/position hold control mode. In addition, the pilots can easily over-torque the rotorcraft, especially if they attempt to match the vertical motion of the deck.

This project seeks to develop advanced control law frameworks and design methodologies to provide autonomous landing (or, alternatively, a high level of control augmentation for pilot-in-the-loop landings). The design framework will focus on some of the most critical components of autonomous landing control laws with the objective of improving safety and expanding the operational capability of manned and unmanned rotorcraft. The key components include approach path planning that allows for a maneuvering ship, high performance station-keeping and gust rejection over a landing deck in high winds/sea states, and deck motion feedback algorithms to allow for improved tracking of the desired landing position and timing of final descent.

2.   Activities this period

In the progress report of period April 2016 – July 2016 a landing path optimization algorithm was presented. The algorithm was able to generate an inertial landing path satisfying requirements. In the implementation, the optimized inertial path generated a position, velocity, and acceleration profile that were used as command in the trajectory following controller. Evaluation on randomized cases revealed that without using any in-time deck state feedback, the success of landing was heavily dependent on the accuracy of the deck motion forecasting. In theory, the forecasted deck state should approach actual deck state as the forecasting horizon decreases during the landing. However, this does not guarantee that the aircraft will make early contact with the deck, prior to the desired touchdown time if the forecasting has some significant error in intermediate times. In this effort period, a hybrid version of the path command implementation was developed [1], which uses both forecasted and instantaneous measurements of the deck state. The hybrid implementation is divided into two phase: 1. Extract relative A-V-P (acceleration, velocity and position) commands by subtracting the inertial A-V-P with the predicted deck state.; 2. Correct the relative path with in-time deck state to reform the inertial A-V-P command. The advantage of the method is in that: if the prediction is accurate, the superposition of relative command and actual deck state perfectly replicates the optimized inertial trajectory. In the case of erroneous forecasting, the reformed inertial command may be distorted from the optimized version, but ensure that there is no early deck

contact. This approach can be used in vertical and lateral axis. The results of simulation for evaluating the hybrid path implementation arre demonstrated in Figure 1-4 and Table 1.
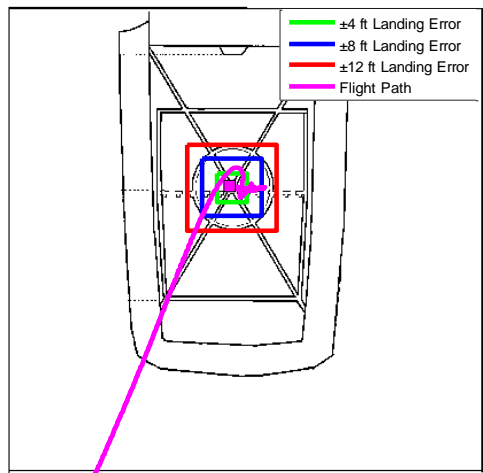

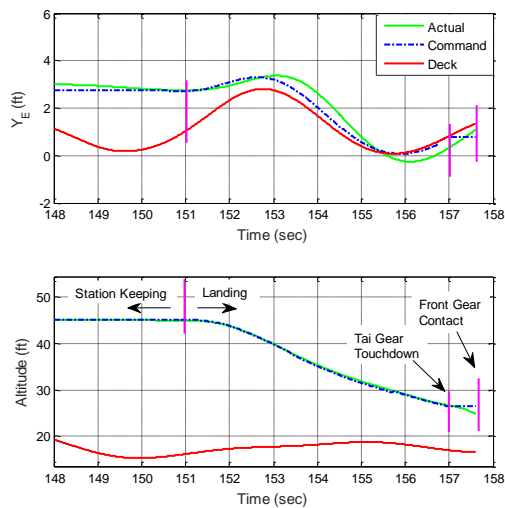Figure 1. View of Trajectory of Approach, Station Keeping and Landing
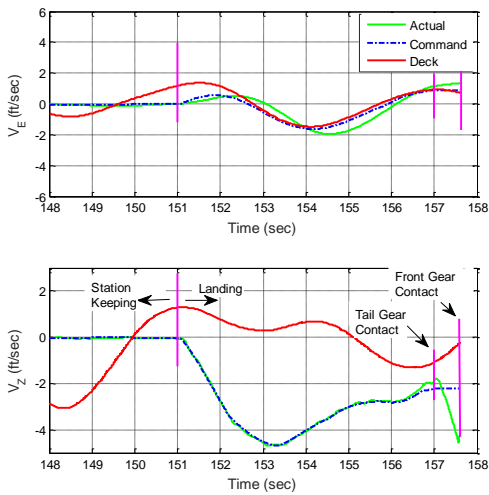

Figure 2. Lateral and Vertical Position of C.G.

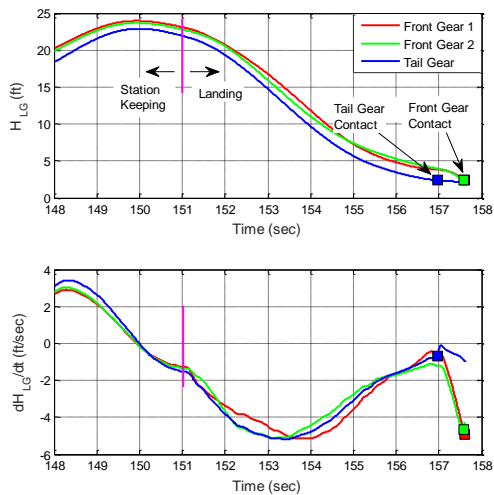Figure 3. Lateral and Vertical Velocities of C.G.

Figure 4. Height and Vertical Velocity of Landing Gear Relative to Deck

Table 1. Landing Quality Metrics

Longitudinal Position Error (ft)	Lateral Position Error (ft)	Lateral Velocity Error (ft/sec)			Vertical Velocity Error (ft/sec)		
		Tail Gear	Front Gear 1	Front Gear 2	Tail Gear	Front Gear 1	Front Gear 2
0.433	0.499	0.226	0.679	0.679	0.6651	4.648	4.919

The hybrid implementation was found to provide very accurate landing position and relatively low velocity at initial deck contact. Initial deck contact is almost always made by the tail gear due to the inherent nose up attitude of the helicopter. Once the tail gear makes contact (almost always with low relative velocity), the control logic must immediately reduce lift so that helicopter firmly pushed down on the deck. Otherwise the position control will behave erratically as the helicopter experiences contact and friction forces through the taiil gear. We term this lift reduction control logic "lift-dumping". However, it is found that after lift-dumping the helicopter descends relatively rapidly and rotates nose down resulting in larger than desired vertical velocity when the front two landing gear make contact. Thirty randomized flight cases were tested and are summarized in Figure 5-6. On the positive side, the final position tolerance for the aircraft CG at touchdown was excellent, with the tail gear touched down softly in all cases. However, these results also show that the vertical impact on the front landing gear was higher than desired.
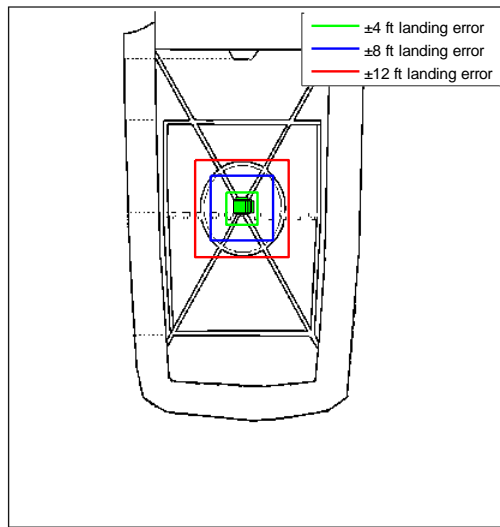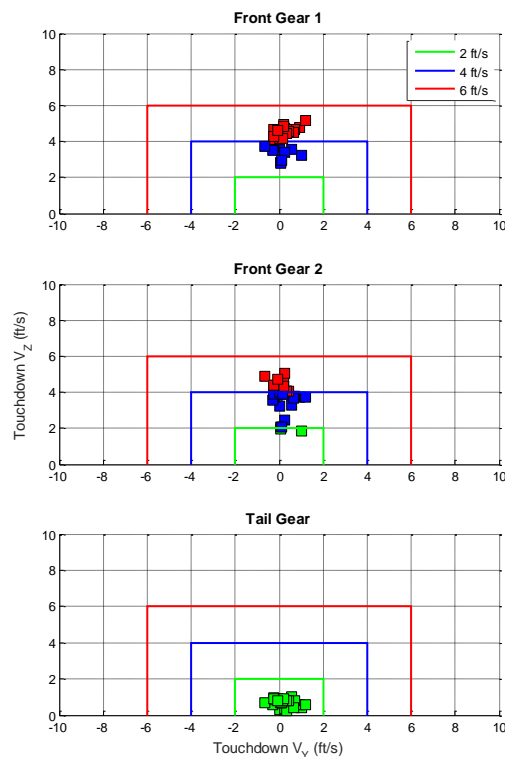

Figure 5. Scatters of Landing Location

Figure 6. Scatters of Touchdown Velocity Error

Various modifications to the lift-dumping control were investigated, such as reducing the collective rate during the lift dumping or phasing in the lift–dumping control over a longer period of time. In many case these strategies resulted in desired performance. However, there were outlier cases with very poor performance when the lift-dumping was executed too slowly. Notably, if the deck accelerated downward soon after the tail gear contact, the tail gear would lift off and then land very hard.

This problem is a consequence of attitude mismatch at touchdown; where the aircraft attitude does not comply with the deck orientation. Attitude mismatch is a common for helicopter; even a land-based helicopter face the problem during landing since the helicopter attitude is not level in hover trim and they sometime need to land on a sloped surface. However, the attitude mismatch is much more complex with a moving landing deck. In high sea states, a quick sealing of touchdown is required to avoid the complex deck-aircraft interactions involving landing gear contact dynamics.

A possible solution to this problem is to place the aircraft parallel to deck plane just before touchdown so that all three landing gear contact simultaneously, and then quickly dump the rotor lift to press aircraft tightly on flight deck. This can be achieved by a quick level-out operation at the moment before anticipated contact. The so called "*level-out*" maneuver cannot occur too early, as the helicopter begins to translate as soon the attitude changes away from the trim. The start time of level-out depends on the quickness of response to attitude command. Since the control law switches from trajectory tracking to attitude command, the aircraft during level-out is expected to drift from the landing center. The level-out must be initiated at a proper time, which cannot be too early to avoid notable drifting, nor to be too late to avoid premature contact. Based on the characteristics of the UH-60 model being investigated, the level-out is initiated 1.0 second before contact.

The level-out control law commands attitude corrections quantitated for removing the difference among heights of three landing gears over deck. The schematic of the geometric parameters of the landing gear is shown in Figure 10:
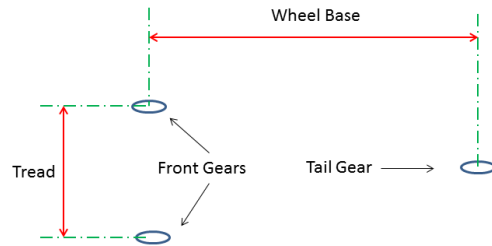

Figure 7. Geometric Parameters of Landing Gears

The amount of pitch and bank angle corrections required to level out the front and tail gear is based on a small angle assumption quantified in Eq. (11) and (12) respectively:

$$\Delta\theta = \frac{(H_{LG1} + H_{LG2})/2 - H_{LG3}}{L_B}$$

(1)

$$\Delta\phi = \frac{H_{LG1} - H_{LG2}}{L_T}$$

(2)

The real-time value of the above corrective attitude angle is fed into longitudinal and lateral ACAH controller to promptly drive the helicopter to the desired attitude. The maximum response quickness allowed by the command filter in the ACAH controller is used. In the meantime, the vertical axis continues descent along the trajectory planned by algorithm presented before. Since three landing gear are designed to hit deck at the same time, the lift-dumping takes place at a fast rate – 20% per second to seal the touchdown as soon as one gear strikes deck. Figures 8 to 13 represent a typical landing with the level-out strategy.
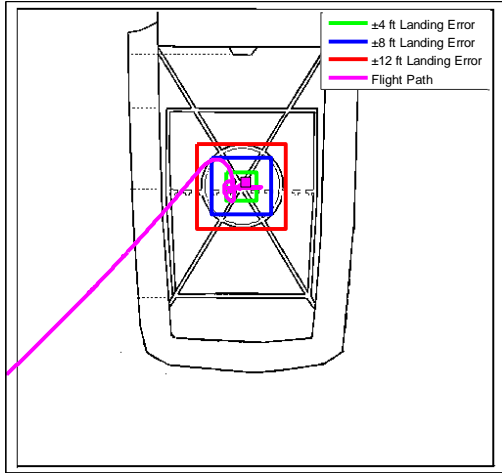
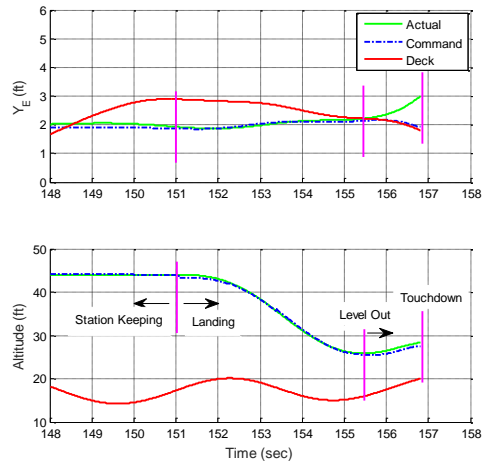Figure 8. Top View of Approach and Landing Trajectory

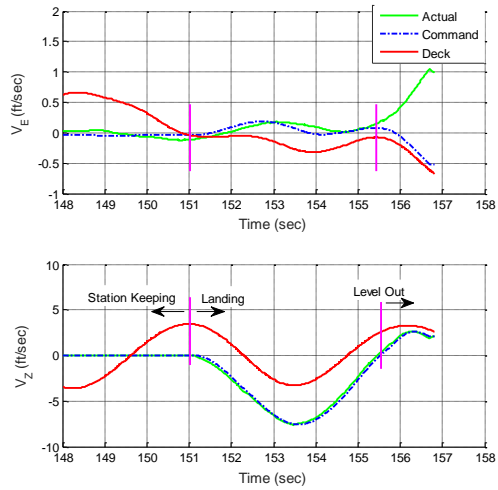Figure 9. Lateral and Vertical Position vs. Time

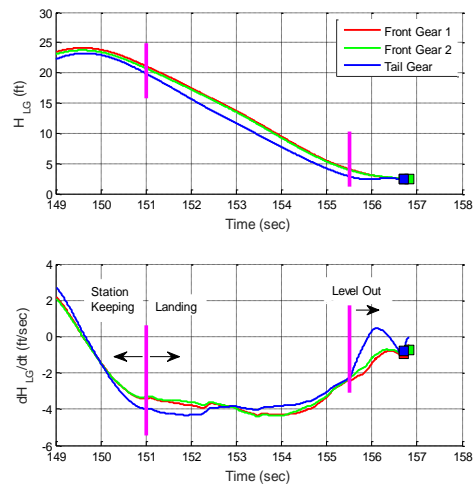Figure 10. Lateral and Vertical Velocities vs. Time

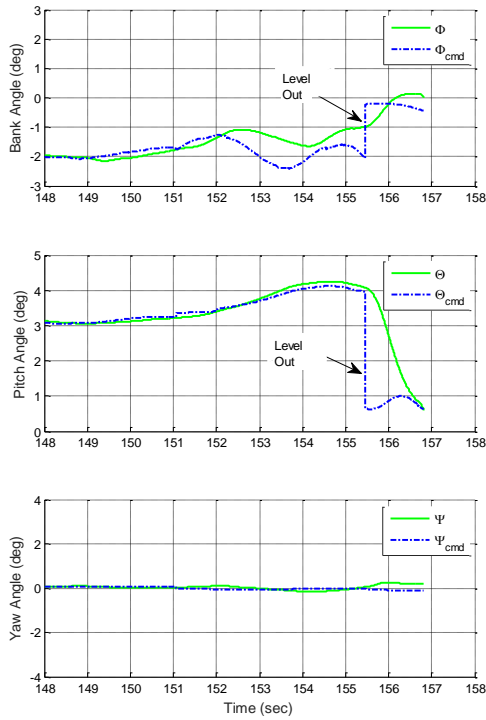Figure 11. Height and Vertical Velocity of Landing Gear Relative to Deck

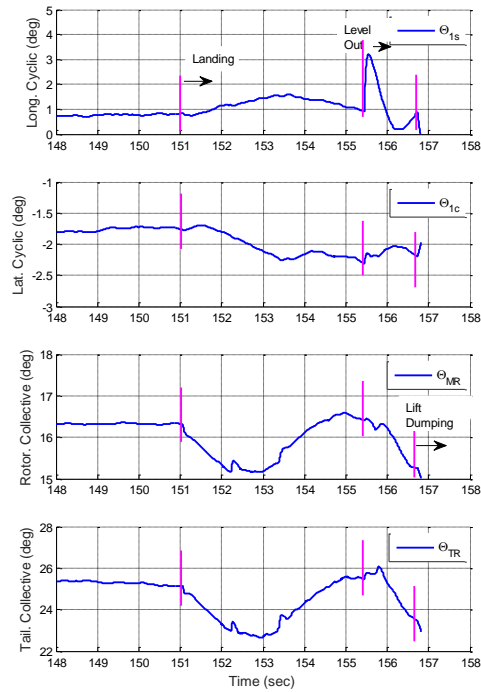Figure 12. Helicopter Attitude Angles vs. Time

Figure 13. Blade Pitch Angles vs. Time

Figure 11 clearly shows the elevation of tail gear during level out, as it is expected. In Figure 12, the vehicle attitude experienced a step-command in the beginning of level-out action, namely - pitch down to elevate tail gear and bank right to elevate left gear. The above control action was also reflected in the control activity in Figure 13. However, the undesired drifting can also be observed in the lateral position plot of Figure 9-10, although the amount was acceptable. Quantitative metrics of landing quality are summarized in Table 2.

Table 2. Landing Quality Metrics

Longitudinal Position Error (ft)	Lateral Position Error (ft)	Lateral Velocity Error (ft/sec)			Vertical Velocity Error (ft/sec)		
		Tail Gear	Front Gear 1	Front Gear 2	Tail Gear	Front Gear 1	Front Gear 2
2.1	1.1	1.635	1.610	1.625	0.553	0.672	0.732

To verify the control strategy and reasonability of parameters, extensive test case with randomized flight conditions were performed, with the results shown in Figures 14-15. The level-out control law successfully addressed the impact on front gears due to sequence of touchdown at a tolerable cost in terms of landing location drifting and lateral speed with respect to the deck.
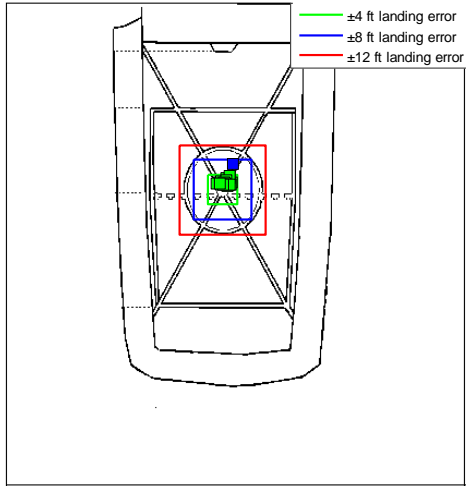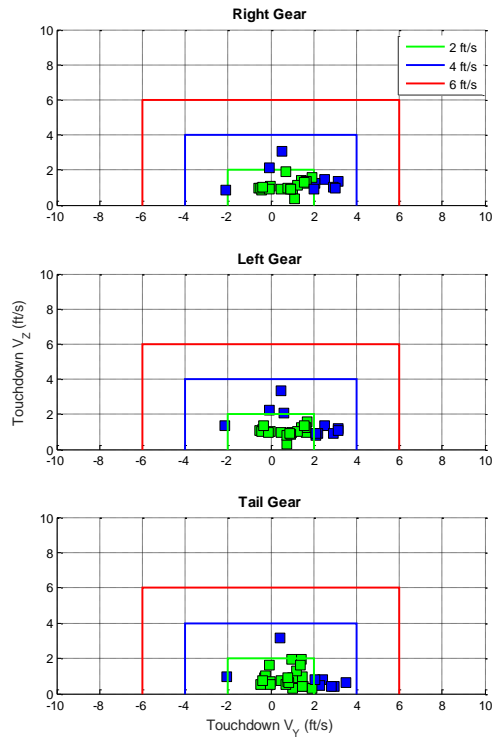
Figure 14. Scatters of The Landing Location

Figure 15. Scatters of Touchdown Velocity Error

Task 13 – Prototype testing and evaluation

ART has completed the enclosure and testing of the integrated model with all historical milestone version of control law. In the frozen configuration, a common outer-loop trajectory tracking and inner-loop ACAH is defined in CSGE, different navigation laws have been expressed either in CSGE or in script. by invoking corresponding switch logics, the following guidance strategy has been enabled: straight-line approach, deck tracking landing algorithm, Rendezvous predictive landing algorithm, B-spine approach path optimization, predictive landing with path optimization. The integrated allows testing and evaluation of inner-loop ACAH, and/or ship board recovery with any of the above guidance law by running the corresponding script. The architecture of control, guidance and navigation is invariant during transplant from one aircraft to another thanks to the nature of DI controller, only need to regenerate the DI matrices for different plant, thus the above integrated model can be quickly replicated on different aircraft for prototype evaluation.

3.   Significance of Results

1) Finished the integrated model and defined the main architecture of control law and interface of communication with external commands. Based on this standard scheme of development, optimized

parameters and/or other advanced algorithm developed in the future can be readily incorporated into the unified testing environment.

2) The hybrid implementation of inertial trajectory is critical in reducing the sensitivity of predictive landing to the accuracy of the deck motion forecasting. The extraction of relative trajectory and modification of the inertial command alleviates the dependency on accurate prediction of terminal deck state.

3) The rolling and pitching flight deck, along with the asymmetric trim of the helicopter raises the issue of the aircraft-deck attitude mismatching problem. The approach of level-out and lift-dumping developed in this effort period uses terminal attitude adjustment to accommodate close to simultaneous contact on all landing gear with the similar amount of soft impact. The level-out operation results in some drifting which undermines the positional precision of the landing, requiring careful timing of the level-out maneuver. This drifting can hopefully to be solved by incorporating attitude expectation into the trajectory planning, and this should be investigated in future work.

4.   Plans and upcoming events for next reporting period

Control law: Effort will be focused on eliminating the drifting of helicopter off landing center. A potential technique is to incorporate attitude expectation into the trajectory planning, this requires a higher order polynomial representation of landing path. The flexibility of developed algorithm for landing path optimization supports this sort of expansion at a cost of increasing the number of free variables.

Optimization of Control Parameters: A multidisciplinary optimization is to be studied to hit the best tradeoff between tracking performance, stability margin and gust rejection in the context of ship board recovery.

5.   References

1. Yang, J., and Horn, J. F., "Landing Path Generation Algorithm for Autonomous Shipboard Helicopter Recovery," 7th AHS Technical Meeting on VTOL Unmanned Aircraft Systems, January 2017, Mesa, Arizona

6.   Transitions/Impact

ART delivered the enclosure of integrated model, all the future development and evaluation will be based on this standard.

Professor Horn presented invited seminar at University of Michigan Aerospace Department on December 1, 2016.

7.   Collaborations

Penn State and ART have collaborated directly with John Tritschler and Sean Roark at NAVAIR. In addition, we are communicating with other Navy researchers pursuing similar projects: Al Schwarz at NSWCCD and Dave Findlay at NAVAIR.

8.   Personnel supported

Principal investigator: Joseph F. Horn

Graduate Students: Junfeng Yang, PhD Candidate

9.   Publications

1. Yang, J., and Horn, J. F., "Landing Path Generation Algorithm for Autonomous Shipboard Helicopter Recovery," *7ᵗʰ AHS Technical Meeting on VTOL Unmanned Aircraft Systems*, Mesa, AZ, January 2017
2. Horn, J. F., Yang, J., He, C., and Lee, D., "Parameter Optimization of Dynamic Inversion Control Law for Shipboard Operations," *American Helicopter Society 73th Annual Forum Proceedings*, Fort Worth, Texas, May 2017.

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11.   Acknowledgement/Disclaimer

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Section II: Project Metrics

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Autonomous Control Modes and Optimized Path Guidance for Shipboard Landing in High Sea States

Progress Report (CDRL A002)

Progress Report for Period: November 10, 2016 to January 9, 2017

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January 29, 2017

Metrics

Number of faculty supported under this project during this reporting period: 1

Number of post-doctoral researchers supported under this project during this period: 0

Number of graduate students supported under this project during this reporting period: 1

Number of undergraduate students supported under this project during this period: 0

Number of refereed publications during this reporting period for which at least 1/3 of the work was done under this effort: 0

Number of publications (all) during this reporting period:1

Number of patents during this reporting period: 0

Number of M.S. students graduated during this reporting period: 0

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Awards received during this reporting period: 0

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